Impact of Li-ion Battery Recycling on The Supply Chain

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Outline

I. Manufacturing Capacity in 2016

II. LIB Materials

III. Current Status and Projections of the LIB

IV. Recycling LIB

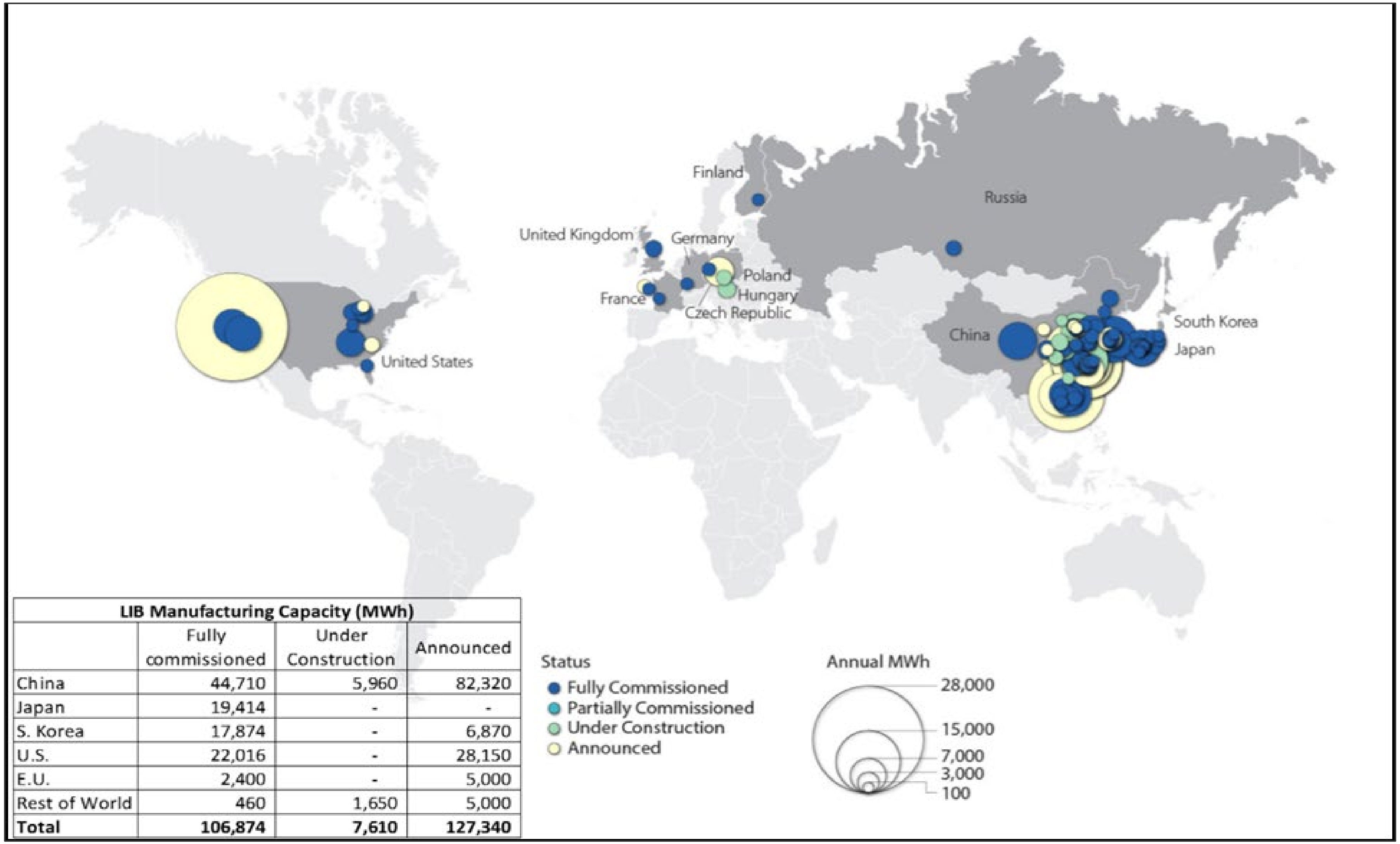
V. Benefits of Recycling (Supply and Demand)

VI. Conclusions

I

Manufacturing Capacity in 2016

Global Automotive LIB Manufacturing Capacity



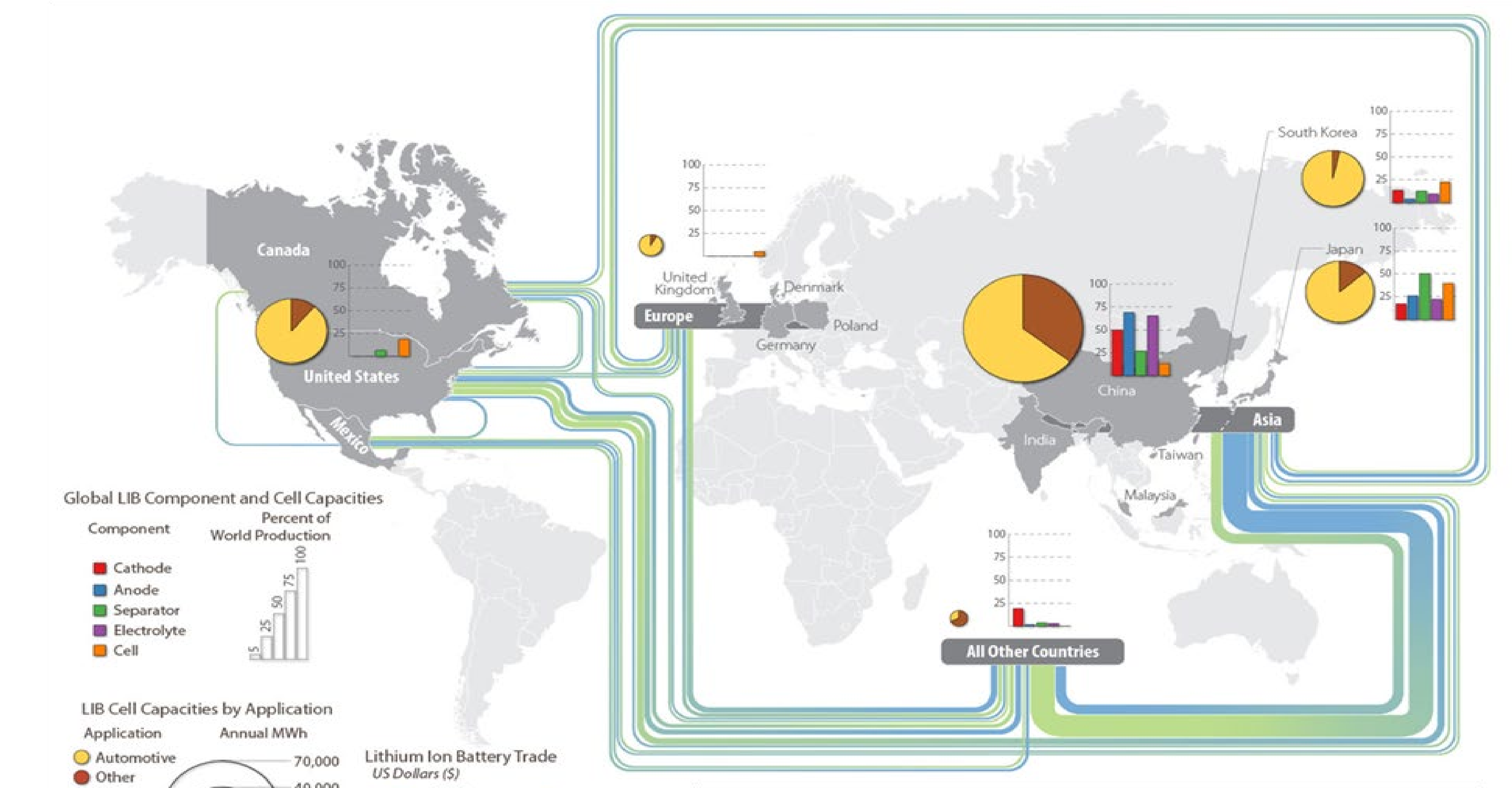
LIB Manufacturing Capacity (MWh)			
	Fully commissioned	Under Construction	Announced
China	44,710	5,960	82,320
Japan	19,414	-	-
S. Korea	17,874	-	6,870
U.S.	22,016	-	28,150
E.U.	2,400	-	5,000
Rest of World	460	1,650	5,000
Total	**106,874**	**7,610**	**127,340**

- LIB manufacturing capacities (including all end market applications) are primarily concentrated in China, Japan, the United States, and Korea.

- Asian countries (China, Japan and South Korea) constitute 84% of global fully commissioned LIB production capacity for all applications in 2016.

sources of data: BNEF 2017; Avicenne 2017; NREL analysis 2018

International LIB Trade Flows



Note: Automotive manufacturing capacities were calculated based on the total production capacity of the studied facilities that make batteries for autos. Some of these facilities make batteries for autos and other applications.

LIB Cell Capacities by Application

	Total LIB Manufacturing Capacity (MWh)	Share of Total Capacity	Automotive LIB Manufacturing Capacity (MWh)	Share of Total Capacity
China	118,234	62.3%	50,670	44.3%
Japan	22,479	11.8%	19,414	17.0%
S. Korea	18,547	9.8%	17,874	15.6%
U.S.	24,766	13.1%	22,016	19.2%
E.U.	2,626	1.4%	2,400	2.1%
Rest of World	3,110	1.6%	2,110	1.8%
Total	**189,762**	**100%**	**114,484**	**100%**

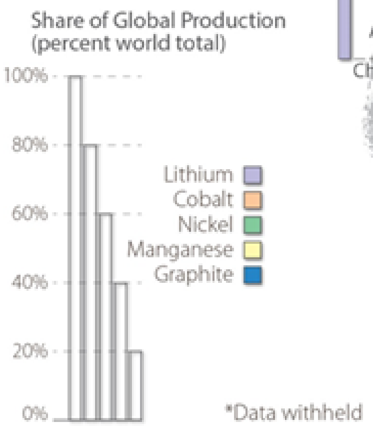
- Asian countries (China, Japan and South Korea) were the key producers of LIB for all applications in 2016

sources of data: Trade Map 2017; BNEF 2017; Avicenne 2017; NREL analysis 2018

II LIB Materials

LIB Supply Chain – Raw Materials

In 2017, 32 countries accounted for all global production of Li, Co, Ni, Mn and Graphite, with 50% of production of each element originating in one or two countries.



In 2017, 32 countries accounted for all global production of key NMC materials

- **43,000 tons lithium**: 44% Australia 34% Chile, Argentina 13%
- **1.2 million tons natural graphite** : 67% China, 13% India, Brazil 8%
- **2.1 million tons nickel**: 11% Philippines, 10% Canada, 9% Russia, 9% Australia
- **16 million tons manganese**: 33% South Africa, 16% China, 14% Australia
- **110,000 tons cobalt**: 59% Democratic Republic of Congo, 5% Russia, 5% Australia

LIB Cathode Chemistries

Modeling of the Amount of Co in Batteries Accounts for Cathode Chemistry

Estimated amount of constituent elements in the different battery chemistries

Battery System Content (g/kWh)					
Battery Type	**Li (cathode + electrolyte)**	**Ni**	**Mn**	**Co**	**Application**
NMC333	130	330	310	330	xBV, Stationary
NMC442	130	440	420	200	xBV
NMC532	130	550	310	200	xBV
NMC622	130	600	200	200	xBV
NMC811	130	800	100	90	xBV
NCA	110	730	0	140	Tesla Cars
LCO	120	0	0	990	Mobiles, Laptops
LFP	75	0	0	0	BYD Cars

Source: BatPac Model v3.1 18OCT2017, Argonne National Laboratory 2018, NREL Analysis

LIB Supply Chain – Raw Materials

World Mine Production (2017)

Element	Reserve (tonnes)	World Mine Production (tonnes)	Percentage Used in LIB	Percentage Used in Electric Vehicle (xEV)	Percentage Used in Other Applications
Cobalt	7,100,000	110,000 (1.5%)†	51%	9.5%	90.5%
Nickel	74,000,000	2,100,000 (<3%)	1%	0.5%	99.5%
Manganese	680,000,000	16,000,000 (2.4%)	~1%	0.1%	>99.9%
Aluminium	n/a	60,000,000† †	n/a	TBD	TBD
Lithium	16,000,000	43,000 (0.3%)	17%	8.1%	91.9%
Graphite	233,201,600	1,183,000 (0.4%)	n/a	6.6%	93.4%

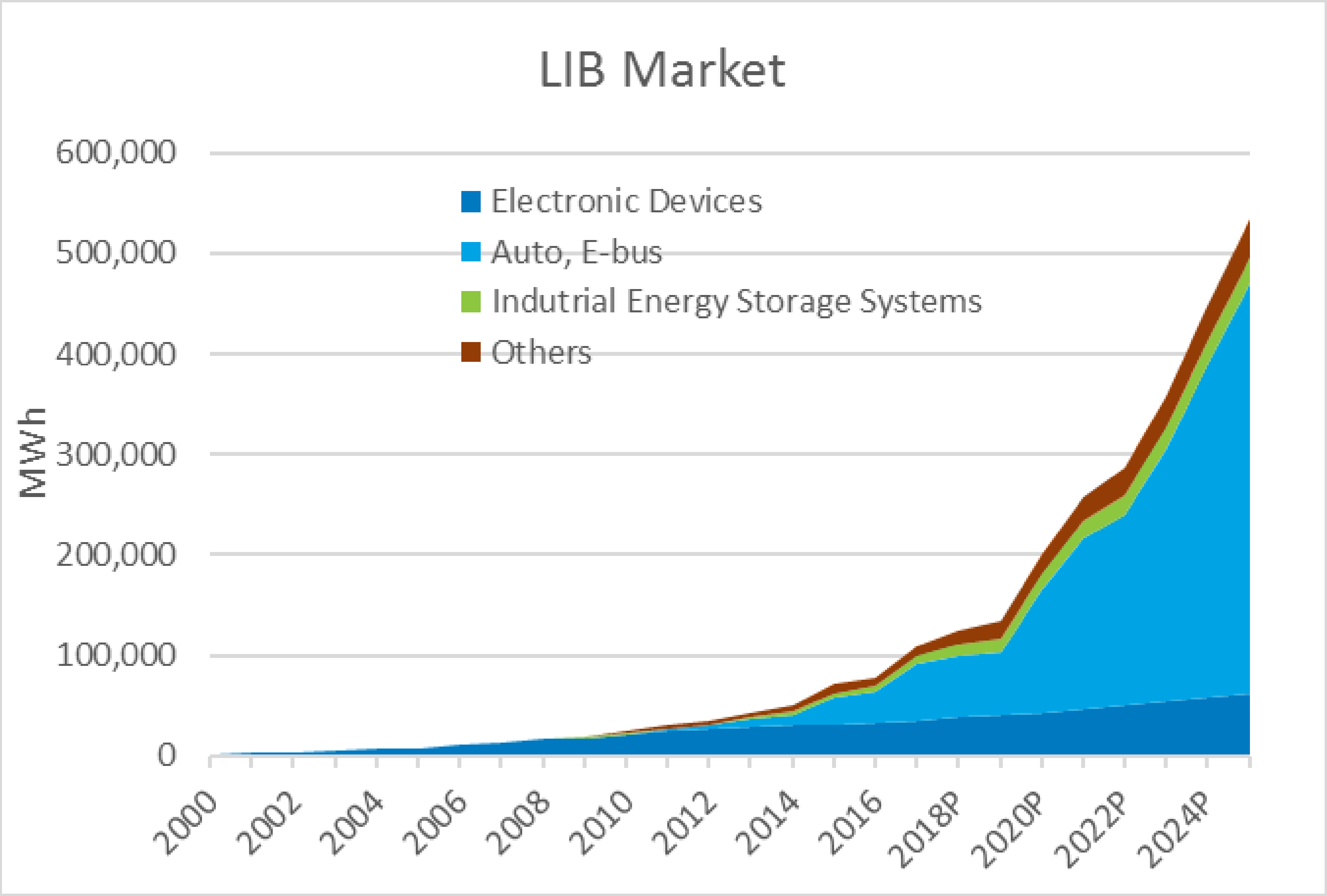
† numbers in parentheses represent percentages of the declared reserve in 2017.

† † World smelter production. Source of data USGS 2016 data, NREL analysis

- LIB manufacturing does not constitute the majority end use of any of these elements
- Based on estimated battery designs and 2017 EV sales figures, approximately 8% of lithium, 9.4% of cobalt, <1% of nickel, <1% of manganese, and 6.5% of graphite produced in 2017 were used for EV battery manufacturing
- Current reserves of these elements continue to change as known deposits are depleted, and as new ones are discovered. These reserves are also based on economically extractable resources – driven by markets and technology
- For all these elements, 2017 mining production represented less than 3% of estimated reserves.

II Current Status and Projections of the LIB

Compilation of Multiple Projections

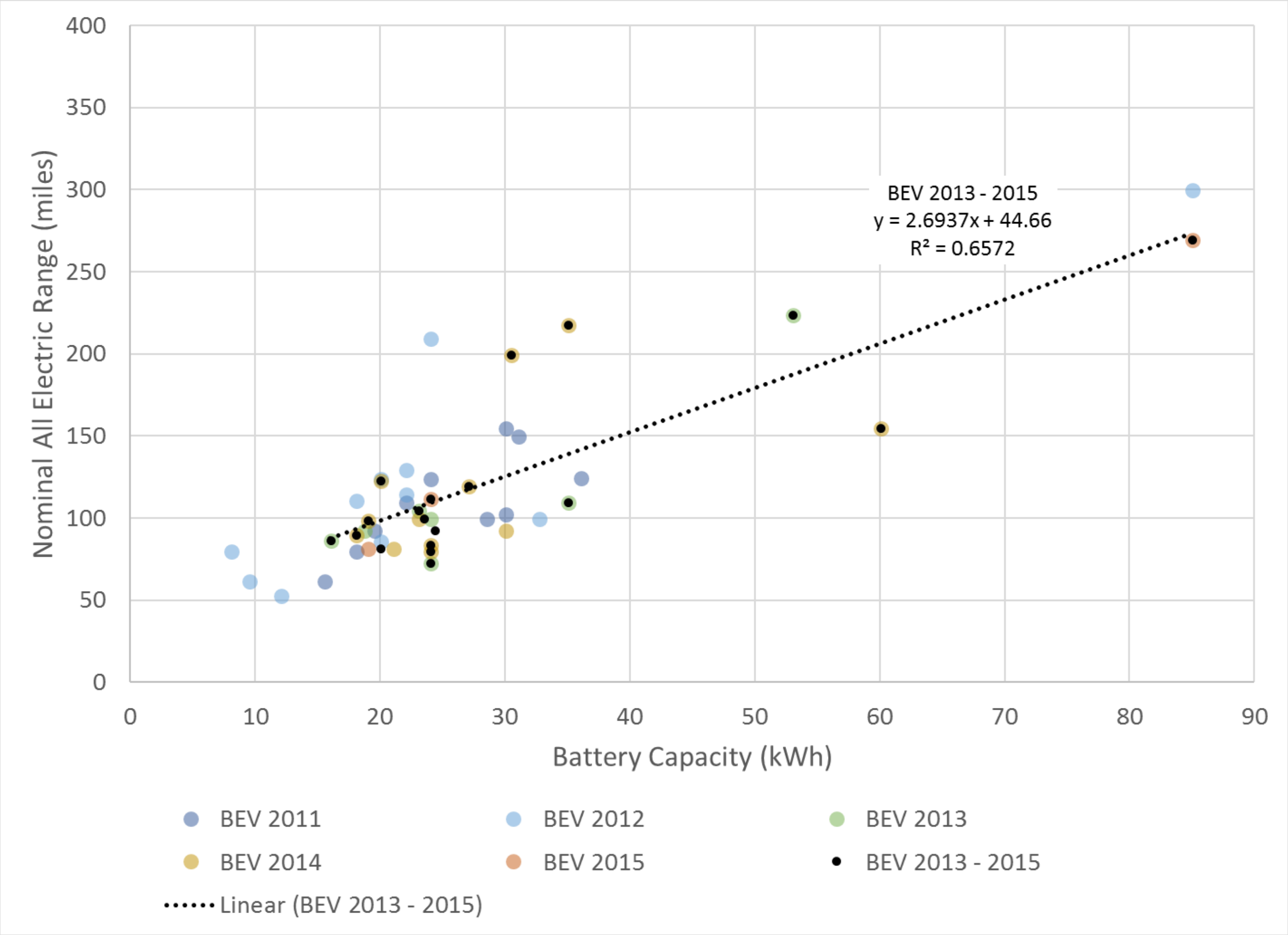


Source of data: BNEF 2017, Avicenne 2017, Navigant 2016, NREL analysis 2018

- Currently, consumer electronics is the biggest LIB application.
- LIB for xBV's will dominate in the near future.

xBV Battery Size in The Future

Example: Modeling of the Amount of Co in Batteries Accounts for Battery Size (kWh)

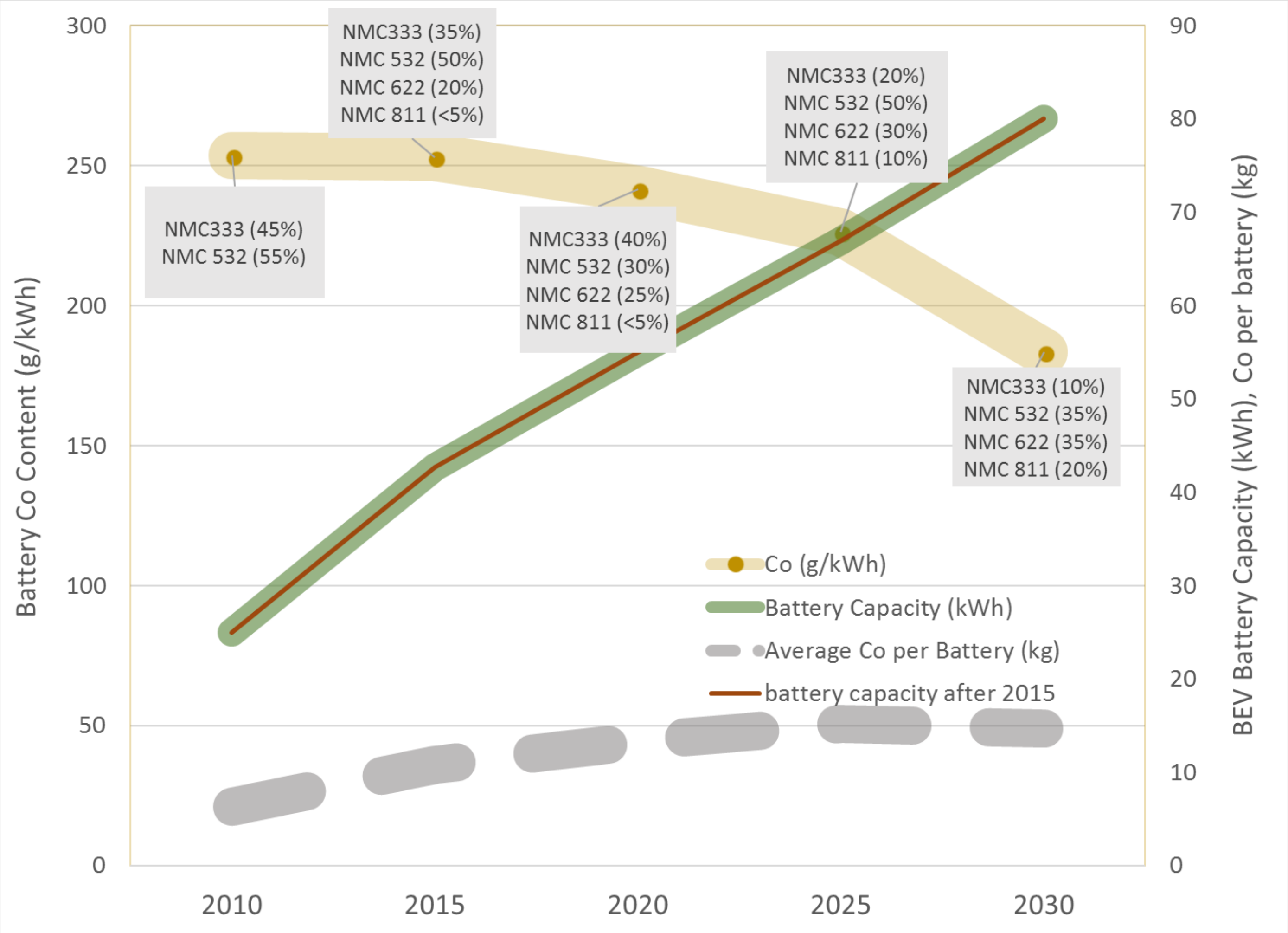


BEV battery capacity is expected to increase to satisfy customer need for a 300 mile range (assumed to correspond to ~ 80 kWh) similar to current internal combustion engines

Source: BEV battery capacity; Bloomberg New Energy Finance

LIB Chemistry vs. Size

The Amount of Co in Batteries is a Combination of Changes in Cathode Chemistry and Battery Size (kWh)

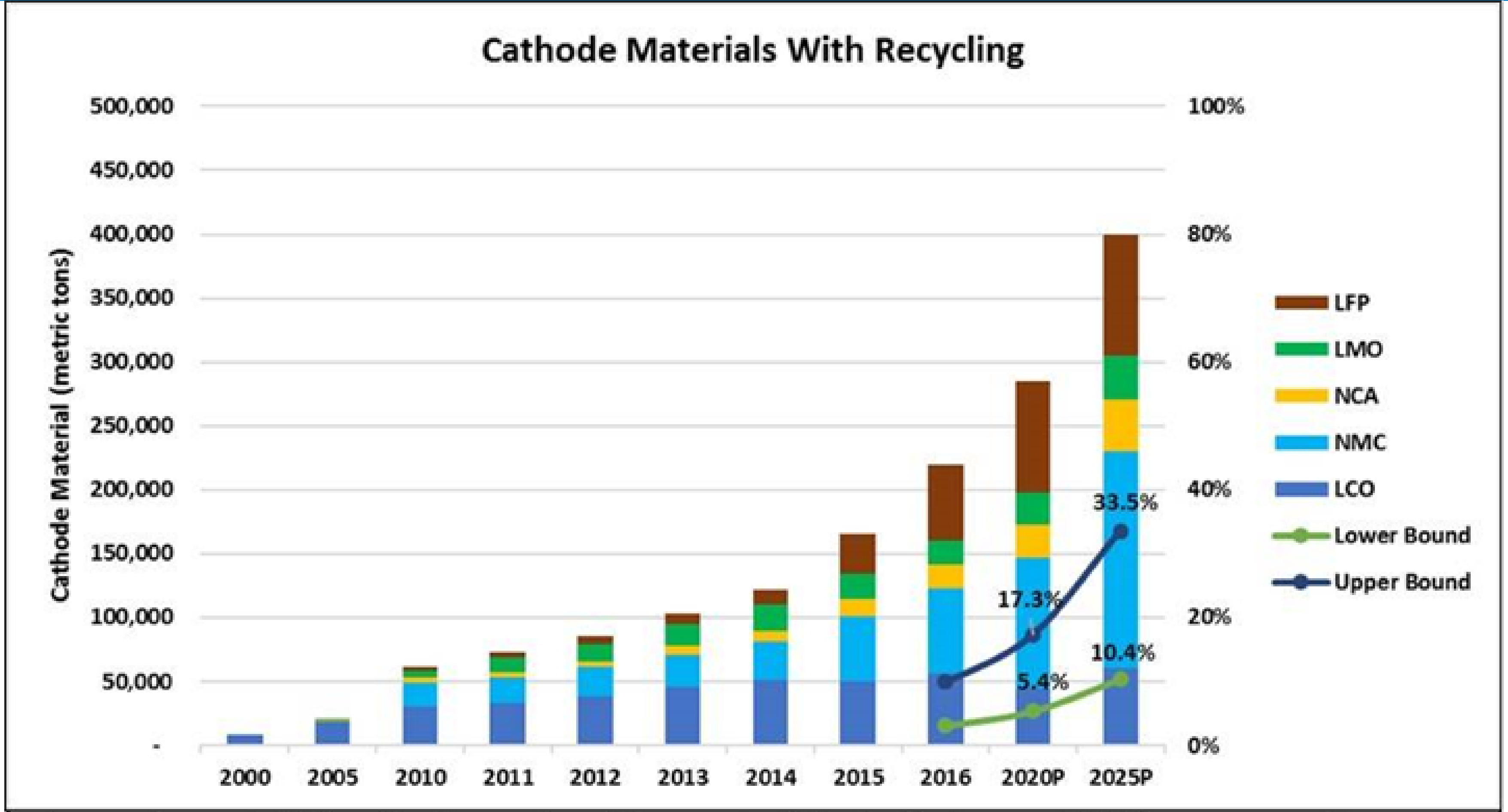


Using cobalt as an example; new cathode chemistries are being developed to reduce Co content, but vehicle batteries are also getting bigger so the amount of Co per battery will continue to increase for some time

Sources: Projections of cathode chemistries; Pillot, Christopher. 2017. "The rechargeable battery market and main trends 2016-2025." International battery seminar and exhibit. Fort Lauderdale, FL., BEV battery capacity (kWh); Bloomberg New Energy Finance to 2015, NREL estimate 2020 – 2030, NREL Analysis

IV Recycling End-Of-Life Li-ion Batteries

xEV LIB Demand vs. Materials



- Lower bound: 50% collection rate of the end-of-life batteries and 50% recovery rate
- Upper bound: 90% collection rate of the end-of-life batteries and 90% recovery rate
- Percentages represent potential of cathode materials demand filled by recycled materials

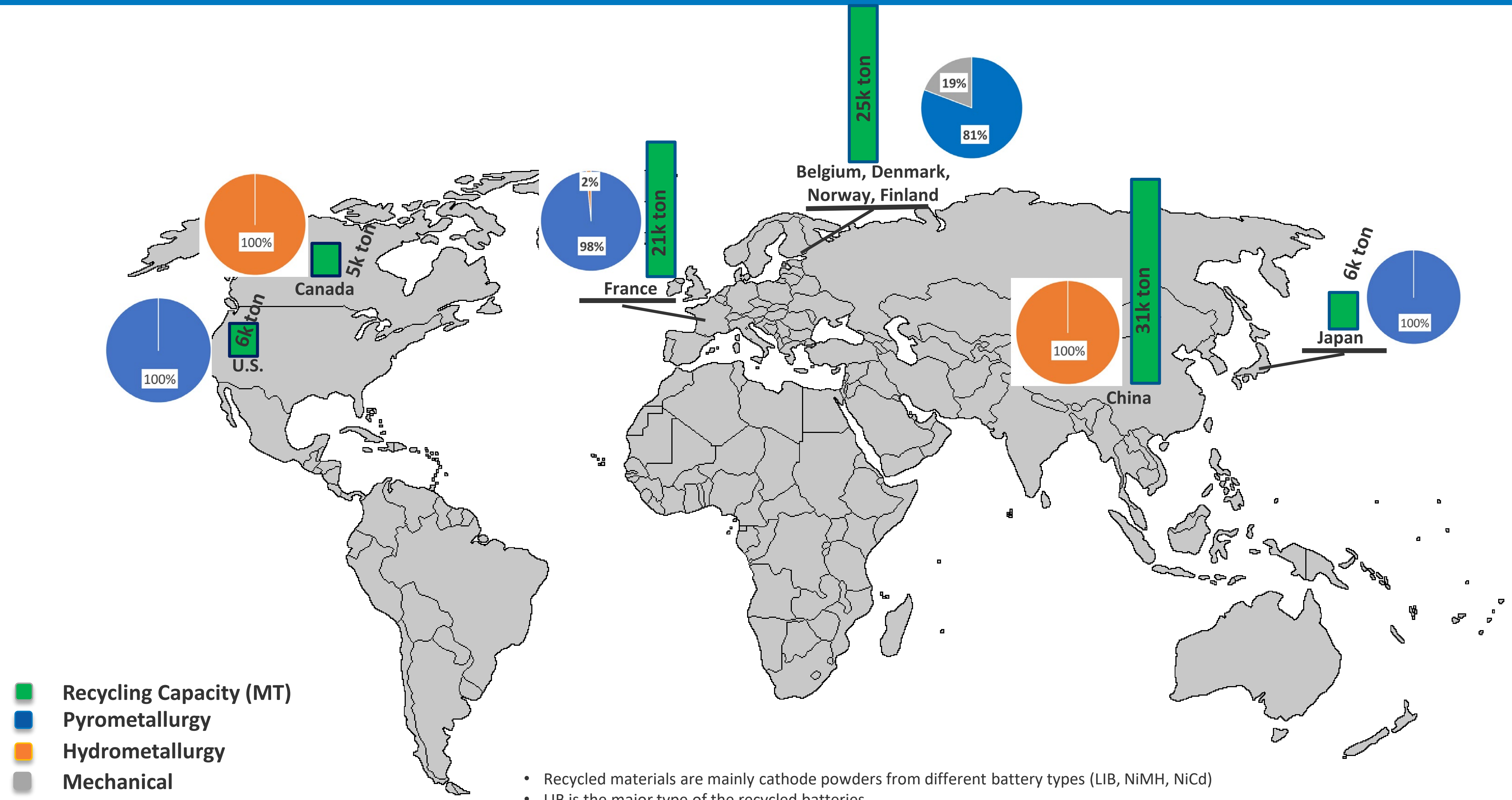
- Total automotive Li-ion battery capacity is expected to exceed 90 GWh by 2020. It will have the largest share among LIB applications followed by consumer electronics
- This requires more than 400 thousand tons of battery materials (Li, Co, Mn, Ni, and Gr) by 2025
- Closed-loop recycling can supply significant amounts of the demand material (up to 30% of the cathode material demanded in 2025)

Source of data: BNEF 2017, Avicenne 2017, Navigant 2016, NREL analysis 2018

Main Recycling Methods

Recycling Method	Pros	Cons	Recovered Materials	Examples
Mechanical Processes	Applicable to any battery chemistry and configuration. Lower energy consumption	Must be combined with other methods to recover most materials	Li_2CO_3	Toxco process
Hydrometallurgy	Applicable to any battery chemistry and configuration	Only economical for batteries containing Co and Ni	Li_2CO_3 Metals (e.g., Al) Co, Ni. Anode is destroyed	Shenzhen Green Eco-manufacturer Hi-Tech Co. (China); Retriev Technologies Inc. (Canada); Recupyl S.A. (France)
Pyrometallurgy (smelting)	Applicable to any battery chemistry and configuration	Only economical for batteries containing Co and Ni Gas clean-up required to avoid release of toxic substances	Co, Ni. Anode and electrolyte are destroyed	Umicore (Belgium); JX Nippon Mining and Metals (Japan)
Direct Recycling (supercritical CO_2)	Almost all battery materials can be recovered	Recovered material may not perform as well as virgin material, mixing cathode materials could reduce value of recycled product	Almost all battery components (except separators)	OnTo Tech (USA)

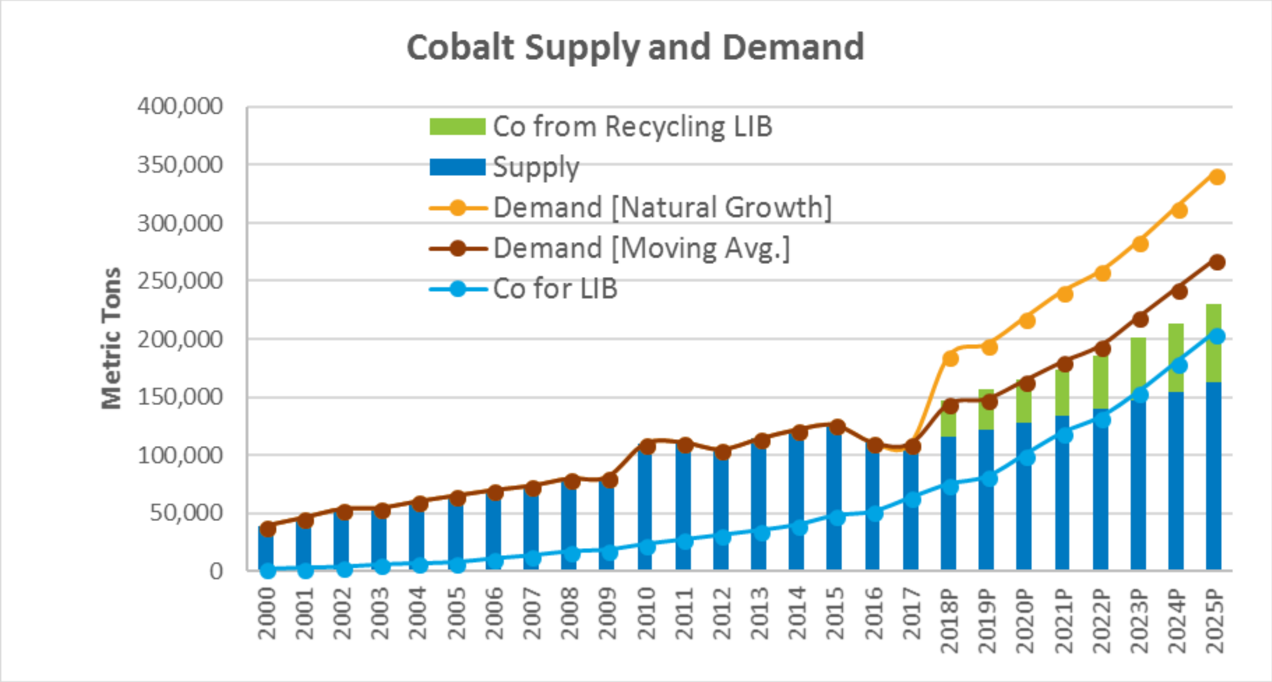
LIB Materials & Recycling in 2016



- Recycled materials are mainly cathode powders from different battery types (LIB, NiMH, NiCd)
- LIB is the major type of the recycled batteries

Source of date: Lv et al., 2018; Heelan et al. 2016; Siret 2012, JRC 2016, NREL Analysis 2018

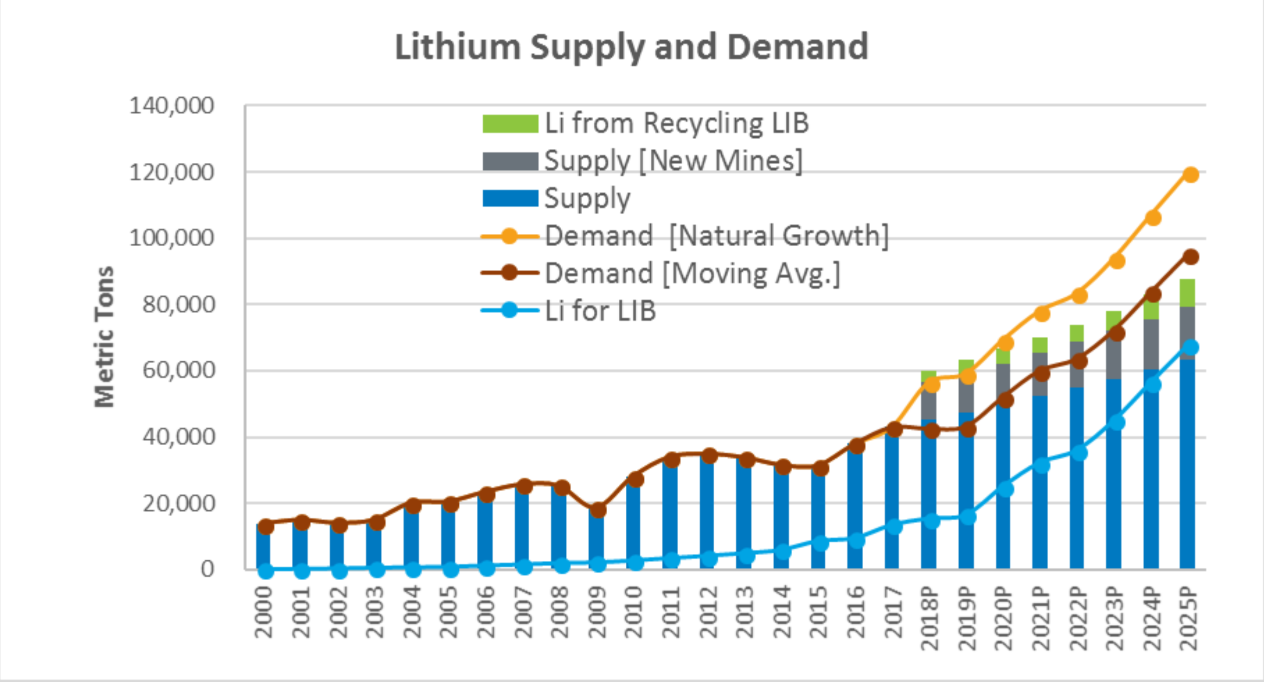
Critical Materials for LIB



Assuming 5% annual growth in mine productions

- Cobalt and lithium are most critical materials for LIB
- Cobalt supply fell short of the demand starting 2017-2018
- This deficit in the supply will impact price of LIB (xBV and all other applications)

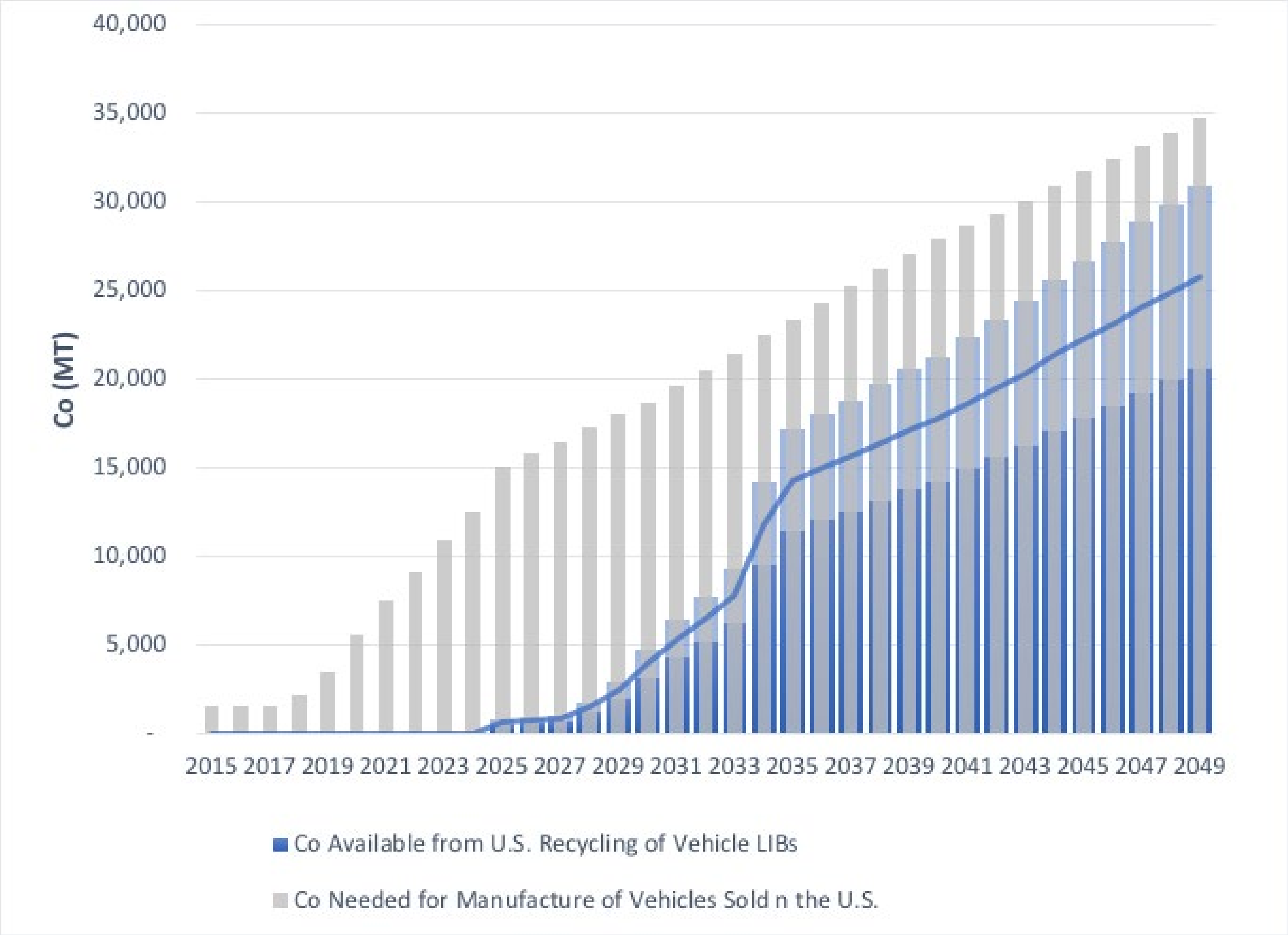
- Recycled cobalt is expected to cover significant part of the demand (~40% of ***automotive*** LIB)
- Lithium is another critical material, but production from new mines in Australia and Chile should cover the increasing demand in the next years.



Assuming 25% annual growth in mine productions

Recursive LIB Recycling Supply Chain Model Development

Amount of battery raw materials that could be derived from recycling of LIB batteries



Spent batteries from vehicles sold in the U.S. could supply U.S-based recycling operations. The amount of material recovered depends on:

- Battery chemistry at the time the batteries were manufactured
- The number of batteries manufactured
- Battery collection efficiency
- Recovery of material from recycling processes

Sources: U.S. vehicle sales projections; EIA AEO Reference Case for LD PHEV and BEV vehicles, modeling from NREL Analysis 2018

V Benefits of Recycling

Benefits of Recycling

Covering part of the demand is just one benefit of the recycling. What about cost and environmental impacts?

	Cost				Energy		$CO_{2\text{-}Eq}$			
	LCO	NMC333	NMC811	LFP	LCO	LMO	LCO	NMC333	LMO	LCO
Pyrometallurgy	38%	6%	5% more		35%		70%	78%		70%
Hydrometallurgy	41%	13%	1%		38%	18%			5%	
Direct Recycling	43%	27%	16%	15%	5%	76%		94%	10%	
Virgin Raw Materials	\$ 62	\$ 45	\$ 40	\$ 32	77MJ/kg	34MJ/kg	200 kWh/kg material	9 kg $CO_{2\text{-}Eq}$/ kg cell	5 kg $CO_{2\text{-}Eq}$/ kg cell	11 Kg CO_2/Kg-material
Sources	Spanganebrger et al., 2018				Lv et al., 2018	Lv et al., 2018	Yazicioglu and Tygat, 2011	Ciez and Whitacre, 2018	Lv et al., 2018	Yazicioglu and Tygat, 2011

Ethical Problem

Child labour in cobalt mines in Congo

Most children earn between 1,000-2,000 Congolese Francs per day (US$1-2). Children who collected, sorted, washed, crushed and transported minerals were paid per sack of minerals by the traders.

Artisanal digger descending into a copper and cobalt mine in Kawama, Congo

(Source of images: inforCongo.com,and Bloomberg)

Key xEV LIB Value Chain Characteristics

LIB Pack Value Chain in 2016 ($US/kWh)

	Raw Materials	Processed Materials	Electrodes	Cells	Battery Pack	TOTAL
VALUE ($/kWh)	$50	$118 [$84]	$28	$146* (cum. $342*)	$74	$416 [$332]
SHARE [With Recycled materials]	12% *[n/a]*	28% [25%]	7% *[8%]*	35% *[44%]*	18% *[22%]*	100% [100%]
CURRENTLY PRODUCED	Globally	Globally	Regionally	Globally	Regionally	
SUPPLY CHAIN ISSUES	• Supply risk of some critical materials (e.g., Co, Li and Gr) • Demand may exceed supply in the near-term	• Critical to produce quality cells • Demand assurance • Recycling can help narrow the gap between supply and demand	• Critical to quality • Regional supply chain clusters in Asia • Emerging supply chains in North America and Europe	• Critical to quality • Regional supply chain clusters in Asia • Emerging supply chains in North America and Europe	• **Proximity to customers**: shipping costs, exchange of technical specifications	

- **Assumed energy storage requirement is 10 kWh for PHEV LIB pack**

*** Factory gate – shipping from Asia to the West Coast of the United States adds approximately $7/kWh (Chung et al. 2015)**

Sources: NREL estimates 2018; Aviceene, 2017; BNEF 2017

VI

Conclusions

Conclusions

- Some materials (e.g., Cobalt and Lithium) used in LIB are critical, and their supplies fall (or will soon fall) short of the demand

- Increasing demand of LIB will be partially but not fully offset by changes in LIB chemistry with lower cobalt and more nickel content.

- Besides the environmental benefits, recycling represents an economic solution for retrieving high value materials from EOL batteries.

- All recycling methods proved to be economic at economies of scale. Cost savings could reach up to 43% of the cost of cathodes made from virgin materials.

Acknowledgment

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- Thank you Samm Gillard, Rachael Nealer and David Howell (Vehicle Technologies Office, DOE)

- Thank you Shriram Santhanagopalan and Anthony Burrell (NREL)

Backup Slides

LIB Recycling Supply Chain – Battery Supply

Estimated battery life ~10 years (150,000 mile)

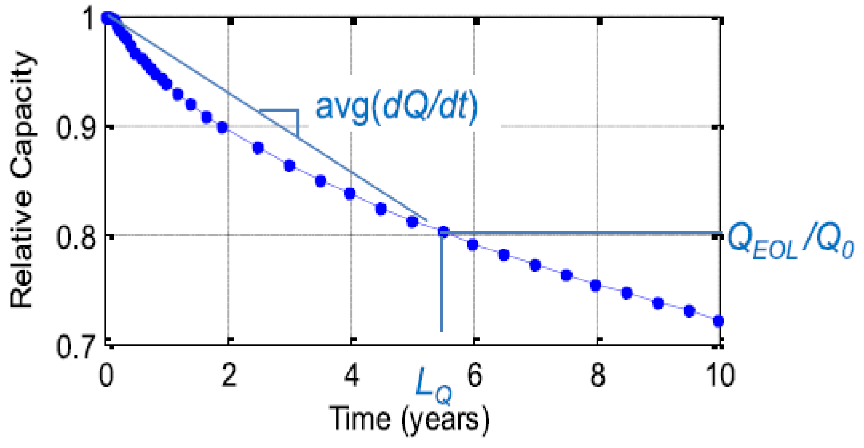


Fig. 2. Finding energy capacity lifetime, L_Q, from NREL's model.

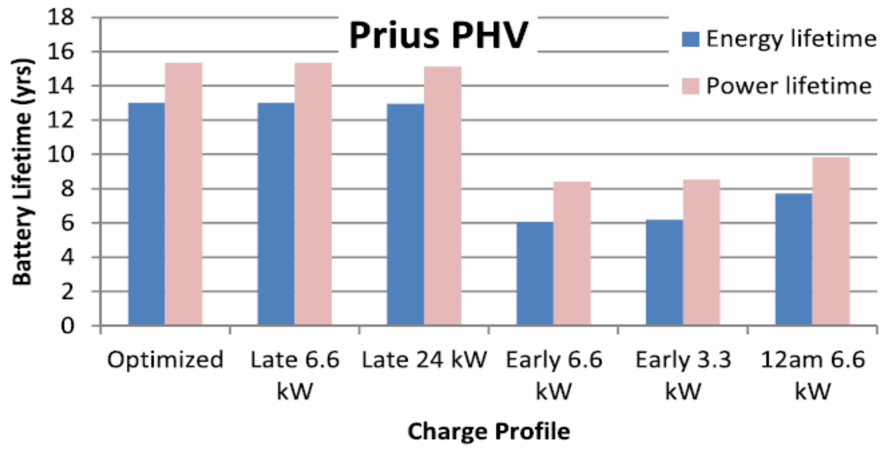


Fig. 9. Prius battery lifetime under various charge scenarios.

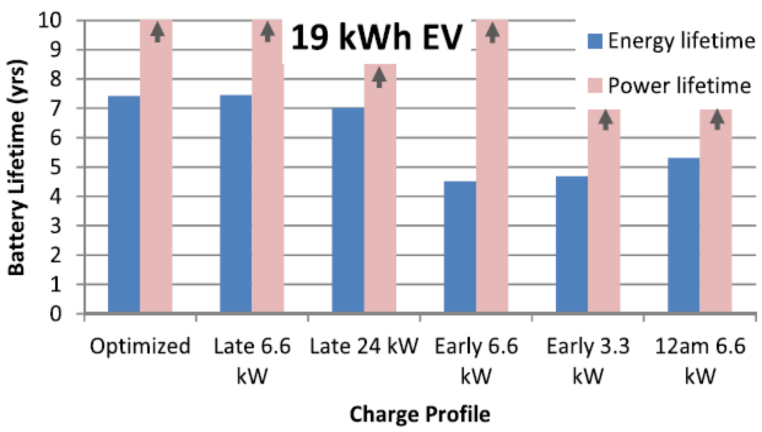


Fig. 10. 19-kWh battery lifetime under various charge scenarios. Power lifetimes truncated.

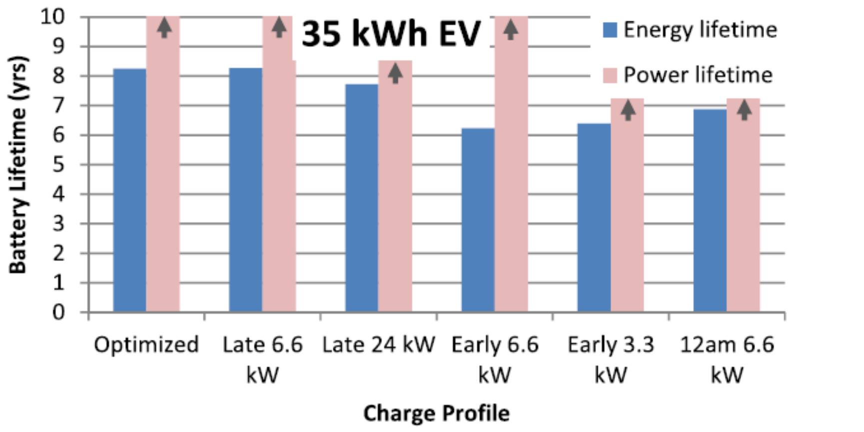
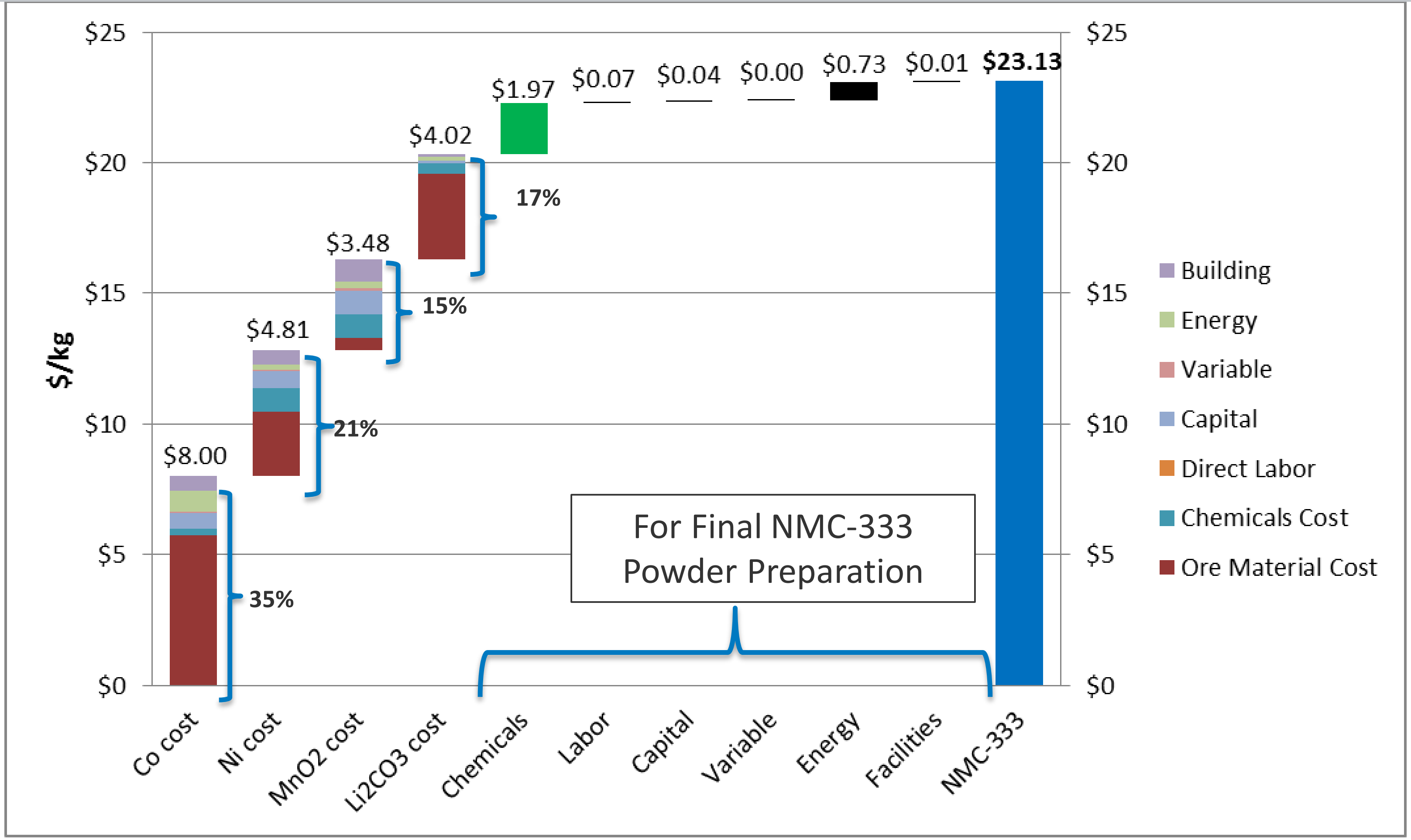


Fig. 11. 35-kWh battery lifetime under various charge scenarios. Power lifetimes truncated.

Hoke et al., 2014

NMC Powder Cost

Ore-grade materials share about 52% of the final NMC-333 material followed by chemicals with 19% cost share. [NMC-333 Formula: $Li_{1.05}(Ni_{1/3}Mn_{1/3}Co_{1/3})_{0.95}O_2$]

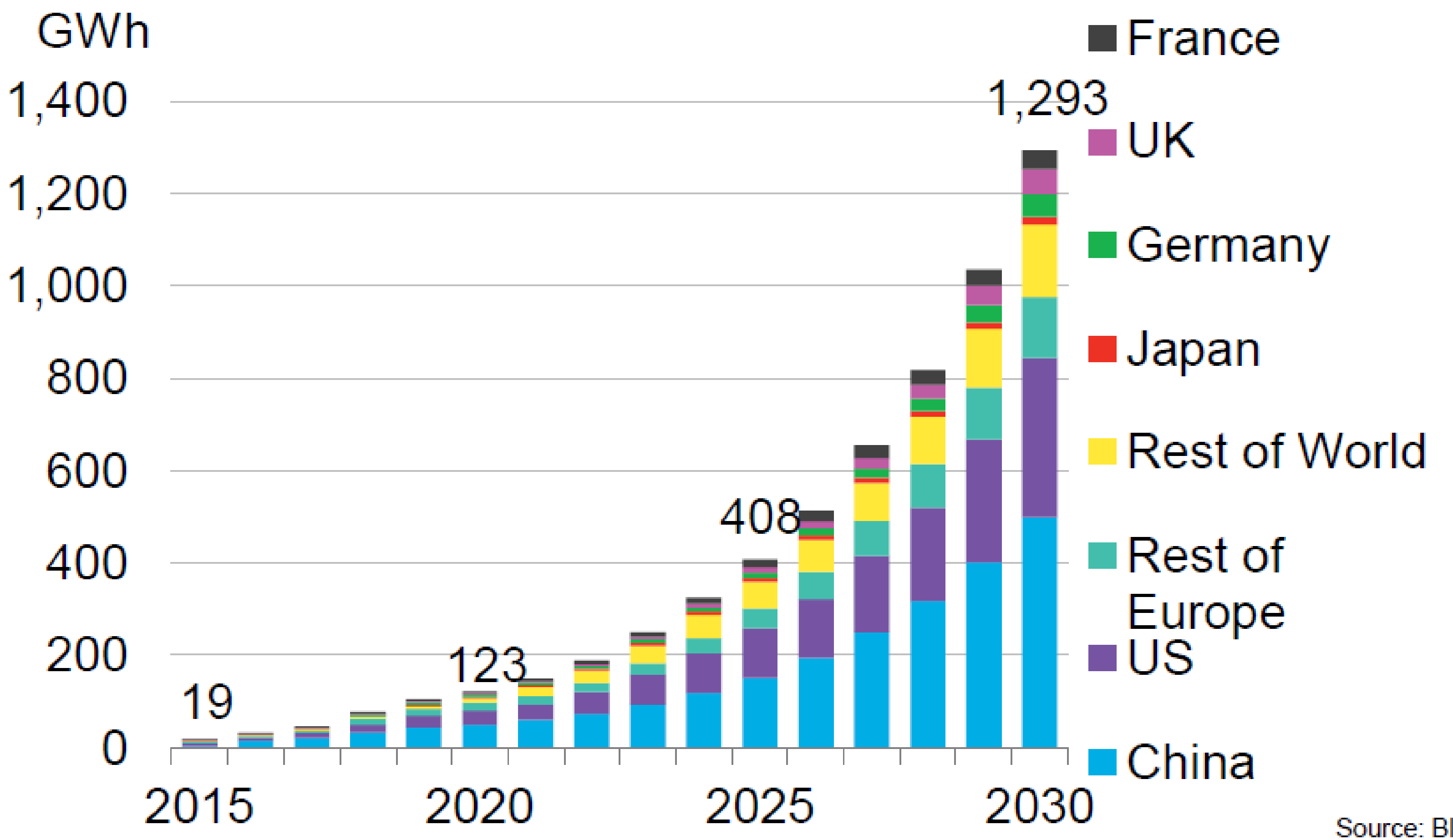


- **Chemical for NMC-333 powder preparation prior to cell manufacturing. Doesn't include cost of chemicals used in purifying Co, Ni, Mn, or Li. (Annual production= 100 ton/yr)**
- **Co cost= $40.30/kg, Ni cost=$24.30/kg, MnO_2 cost= $12/kg, Li_2CO_3 cost=$9.72/kg**

Projections of xBV

China, United States and Western Europe are the key markets for xBVs

Forecasted demand for lithium-ion batteries from EVs, 2010-30 (GWh)



Source: Bloomberg New Energy Finance.

BNEF 2017

Thank You
Questions

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